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Billy W. Loo, Christopher P. Cork, and
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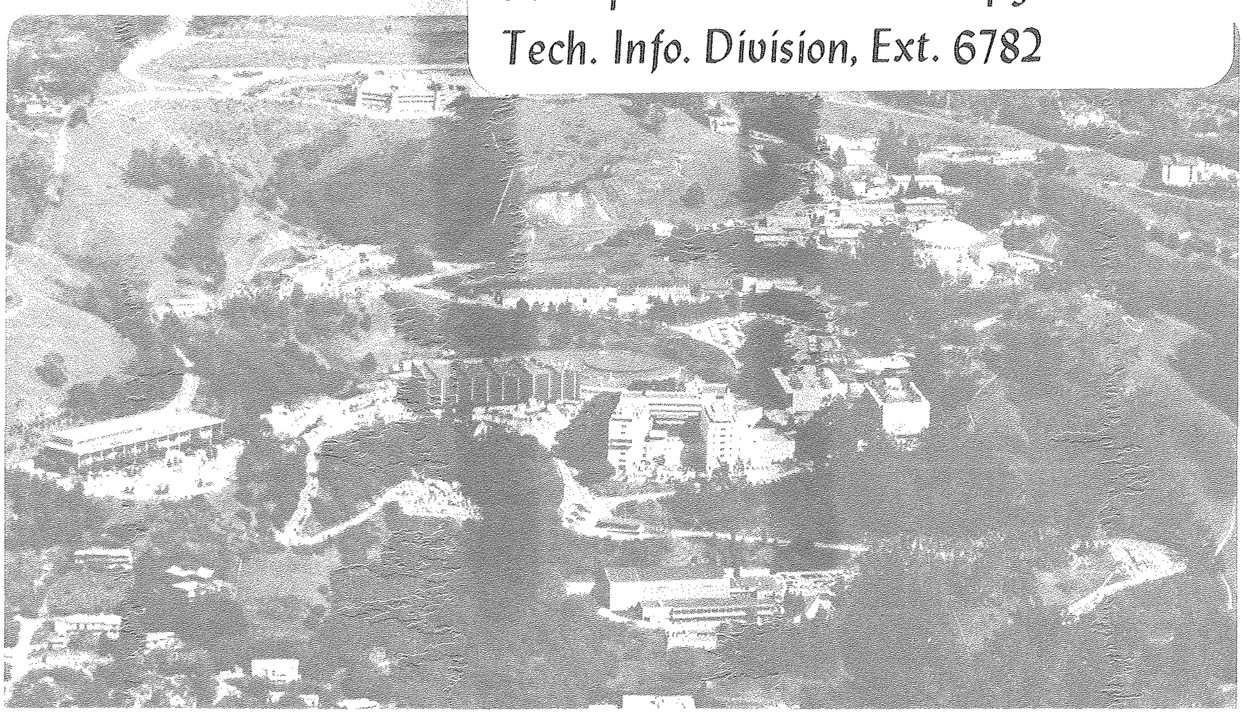

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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ABSTRACT

A generator for delivering a controlled number of carbon fibers of prescribed uniform lengths for the purpose of on-line detector calibration is described. Results showed that it is feasible to generate carbon fibers from about 5 mm long down to 30 μm or less with an accuracy of approximately 5 μm.

INTRODUCTION

Over the past decade, there has been a dramatic increase in the use of high performance composite materials. In particular, because of their broad range of desirable properties such as: a) high tensile strength and modulus, b) light weight, c) resistance to creep, fatigue and corrosion, d) low x-ray absorption and e) thermal expansion coefficients, carbon fiber (including graphite) filled composites are expected to replace a significant amount of the steel, aluminum, and titanium alloys used in the aerospace, sporting goods, and transportation industries.

A potential problem related to the extensive use of carbon fiber composites is the release of individual carbon fibers into the atmosphere as the result of fiery accidents or improper waste disposal. Since carbon fibers are good electrical conductors, they may lead to adverse performance or even destruction of electronic and electrical equipment (NASA 1978). In order to monitor the concentration and fiber length distribution in the air, sampling and measurement instrumentation that is specific for carbon fibers needs to be developed. This in turn calls for the development of carbon fiber generators for detector characterization.

A list of existing carbon fiber monitors has been described by Newcomb (1980). These are mostly suitable for measuring fibers over 1 - 2 mm long. Analysis of burn test results, however, indicated that over 70% by weight of the single fibers released from the burning of composites are in the submillimeter range (Bell, 1979). The electrical and perhaps even health effects of short fibers have not been thoroughly investigated. Since fibers of over 1 mm can be chopped fairly readily by mechanical means (Newcomb, 1980), it is our objective to develop a device for generating monodisperse carbon fibers from several mm long down to arbitrarily short fiber lengths for the purpose of precise calibration of detector performance.

METHOD

Uncapsulated carbon fibers are generally available in the form of long filaments with a diameter of approximately 10 μm. With the premise that the fibers are to be generated for the absolute calibration of detector efficiency and response, we have chosen to cut the fibers individually with a laser beam. In order to avoid any fiber loss, agglomeration or breakage, these freshly cut fibers are introduced immediately into the detector via a carrier air stream.

Figure 1 shows one end of a fiber holder which is a precision straight edge in which 20 semicircular recessed areas have been machined. A single fiber some 15 cm long is aligned along two end pins on the holder and stretched across these recesses under very slight tension. The fiber is then held in place with a drop of diluted water soluble glue at each contact spot between the recesses. By mounting the fiber holder on a three-dimensional translational stage, the fiber can be brought into the arc of focus of a sweeping laser beam. A cut is first made at one end of the fiber segment in the recessed area where the laser beam traverses. Since the fiber segments are very rigid and straight, the length of the fiber to be generated is determined by the movement of the fiber holder between successive passing of the laser beam across the fiber axis. The micrometer which controls the motion of the translator stage along the direction of the fiber axis is driven with a stepping motor. Thus the length of fibers is precisely determined by the number of increments of the stepping motor. Using a motor of 200 steps per revolution and a micrometer of 635 μm per turn, each step then corresponds to a translation of 3.18 μm.

An argon ion laser (Coherent Radiation Model CR-5†) is used as the light source. For the purpose of achieving a sharp cut without significant heat conduction along the fiber, a very small beam spot with high power density will be required. In the limit of diffraction focusing, the approximate 3% irradiance contour of the focal cylinder can be described by (Schwiesow, 1969):

$$W = 2.4\ \lambda\ \left(\frac{F}{D}\right) \tag{1}$$

and

$$L = 16\ \lambda\ \left(\frac{F}{D}\right)^2 \tag{2}$$

where W and L are the diameter and the depth of field of the focal cylinder respectively. The focal length of the lens is represented by F and the diameter D of the incident beam is determined by the $1/e^2$ truncation points. The wavelength of the laser light is denoted by λ.

A schematic of the laser optics is illustrated in Fig. 2. The incident laser beam is expanded to about 6 mm and focused by a plano convex lens of 50 mm focal length. A pivoted piece of glass (3 mm thick) is used as a beam shifter such that when it is oriented in the vertical position, the focus of the beam lies on the optical axis about 0.5 mm below the fiber. As the beam shifter is rotated through an angle θ of about 45°, the focal point is translated vertically to a point about 0.5 mm above the fiber. The position of the fiber holder is adjusted such that the fiber will intersect the center of the focal cylinder as it passes through. Thus, by a repeated sequence of fiber translation and beam shifter rotation, segments of fiber are released and allowed to flow into the detecting instrument. This method of course lends itself very readily for automation.

RESULTS AND DISCUSSION

Tests have been performed on generating some carbon fibers supplied by the Great Lakes Carbon Corp. (Fortafil 3)[†]. To achieve a clean cut, the high power beam must intersect the fiber within an appropriate time interval. It was found that with the beam shifter rotating at the angular velocity of about 6 rad/sec and a laser beam power of 1 watt, fibers can be readily generated. In practice, reliability is assured by using 2 watts of laser power. Since the argon laser wave length is 0.5145 μm, according to equations (1) and (2) the spot diameter and the depth of field are expected to be 10.3 μm and 572 μm respectively. The corresponding power density is 2.4×10^6 watt/cm^2 and the transit time of the beam over the fiber diameter of about 10 μm is 67 μs.

The rate of fiber generation is typically one to two fibers per second and can reach a somewhat higher rate when the sequential operation of beam shifter rotation following each prescribed number of stepping motor advances are fully automated. The amount of fiber that can be conveniently generated is insufficient for effect studies. On the other hand, a small amount of fiber with accurate control on both length distribution and number concentration is quite adequate for instrument calibration purposes.

Sample fibers from the generator have been collected on filters and their lengths measured by a microscope equipped with a digital micrometer (Colorado Video, Inc. Model 305†). The results of monodisperse carbon fiber generation are summarized in Table 1. For a given number of stepping motor advances, the measured average fiber length L and its standard deviation σ_L are recorded. These fiber samples ranging from 1009 μm down to 32 μm in length are illustrated in Figures 3 - 8.

The difference ΔL between the fiber holder advance L^* and the actual fiber length L indicates the amount of fiber that has been vaporized by the laser beam. Note that the standard deviation σ_L and ΔL are not a function of fiber length and their average values are 4.4 μm and 16 μm respectively. This observed ΔL of 16 μm is consistent with the expectation from the calculated minimum beam spot of 10.3 μm assuming diffraction limited focusing. Further evidence regarding the size of the beam spot can be seen from Fig. 9 in which two fiber segments are still barely linked as a result of an incomplete cut.

†Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

It is noted that the Fortafil 3 carbon fiber used has an irregular internal cross-section that resembles a pair of round fibers bound together and results in a width that varies from about 9 - 15 μm depending on orientation. Under higher magnification, some of the inhomogeneous structure is revealed where the center bonding material is vaporized faster than the fiber cores and results in an indentation at the end of the fiber as shown in Fig. 10. Due to such inhomogeneity, the fiber tends to split into two as fiber length approaches 30 μm or shorter.

In conclusion, we have demonstrated that carbon fibers of precisely controlled number and length can be generated with the aid of a finely focused laser beam. By sweeping the beam over a small distance, critical alignment between the fiber and the beam optics can be relaxed. Even with somewhat irregular fibers, the lengths of fiber can be controlled to within 5 μm for any fiber length 5 mm down to about 30 μm. With uniform fibers, it is believed that even short fibers with an aspect ratio approaching unity can be generated.

ACKNOWLEDGEMENTS

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NASA (1978) "Carbon Fiber Study" NASA Technical Memorandum 78718, May 1978.

Newcomb, A. L. Jr. (1980) "A Carbon Fiber Exposure Test Facility and Instrumentation" NASA Technical Memorandum 80220, Aug. 1980.

Schwiesow, R. L. (1969) Journal of the Optical Society of America 59 No. 10, Oct. 1969, p. 1285.

Table 1. Results of monodisperse carbon fiber generation.

Number of Motor Steps	320.0	160.0	80.0	40.0	20.0	15.0	
Holder Advance L^* (μm)	1016.0	508.0	254.0	127.0	64.0	48.0	
Fiberlength L (μm)	1009.0	486.0	237.0	111.0	44.0	32.0	
σ_L (μm)	5.1	7.8	3.1	3.1	3.1	4.5	σ_L(avg) = 4.4
$\Delta L = L^* - L$ (μm)	7.0	22.0	17.0	16.0	20.0	16.0	ΔL(avg) = 16.0

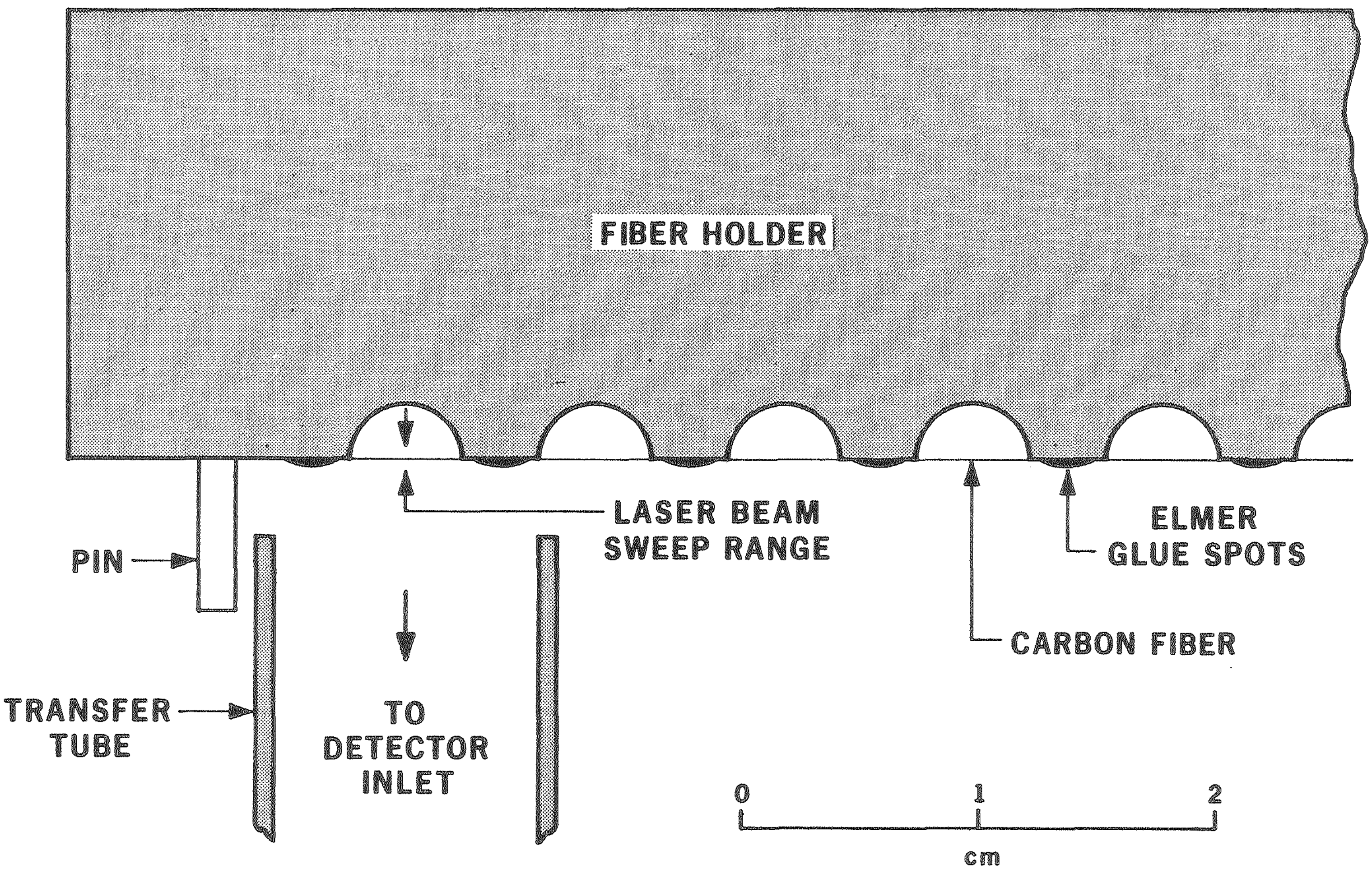

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Fig. 1. Details of a carbon fiber holder.

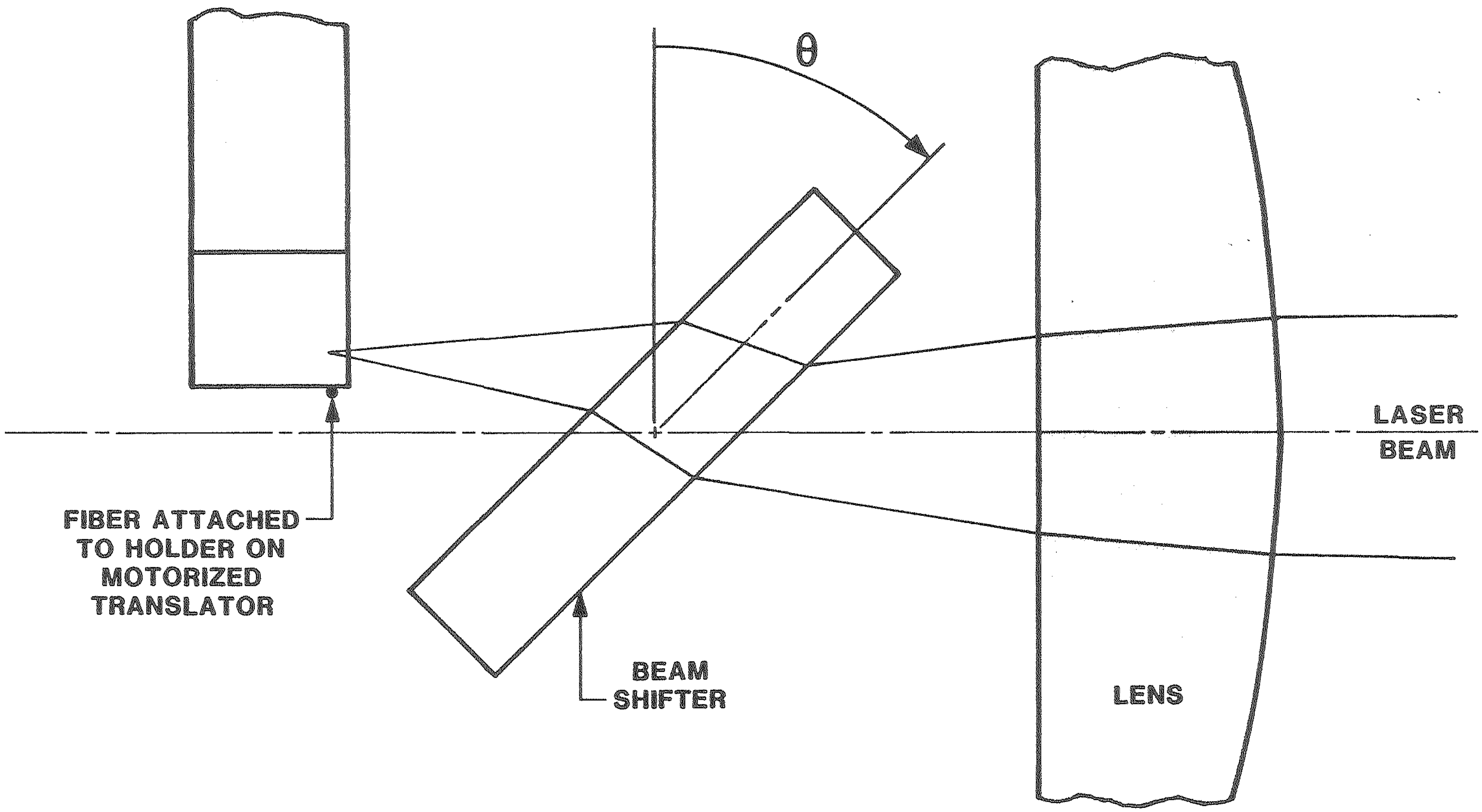

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Fig. 2. Schematics of laser optics (not to scale).

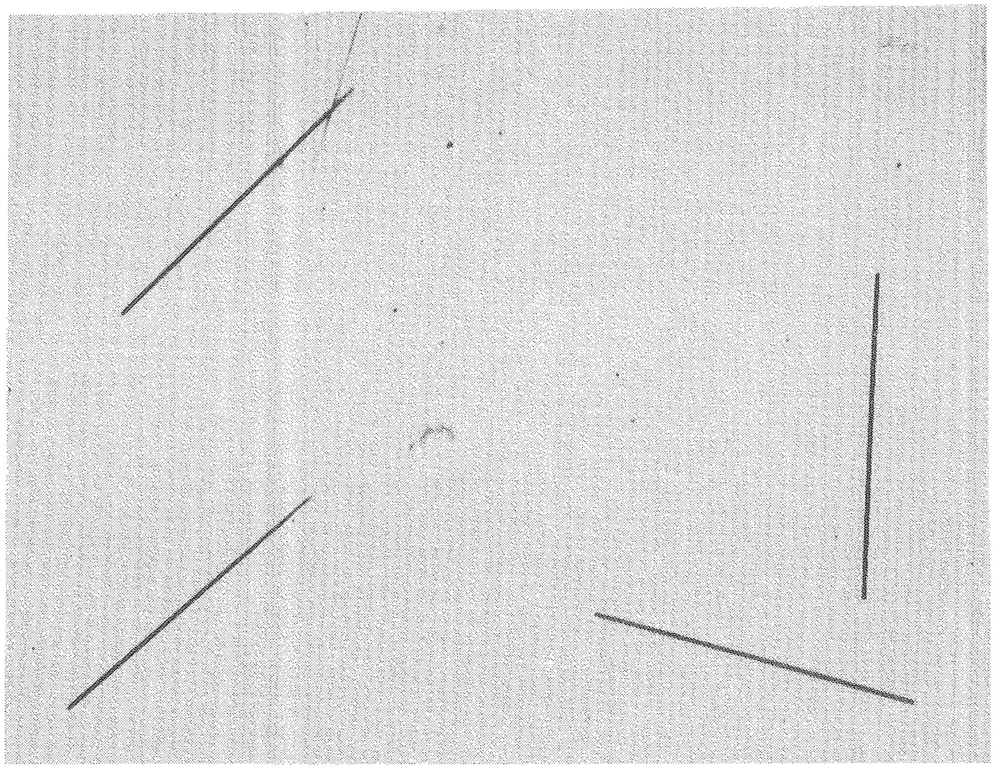

Fig. 3. 1.009 mm fibers.

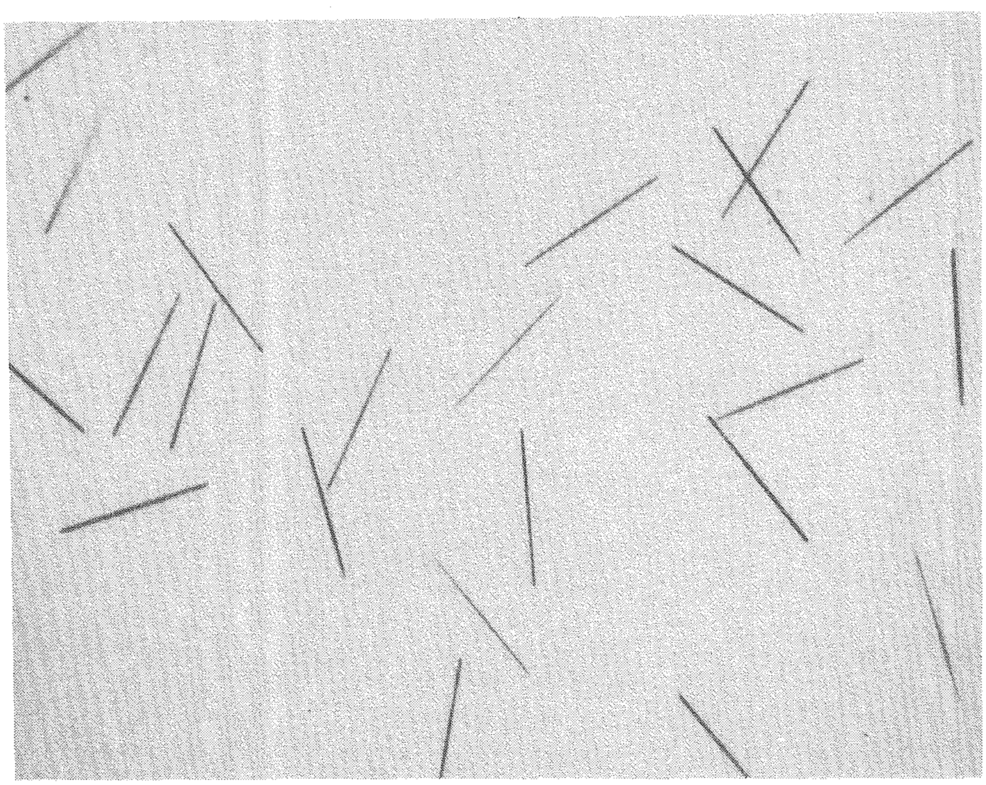

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Fig. 4. 0.486 mm fibers.

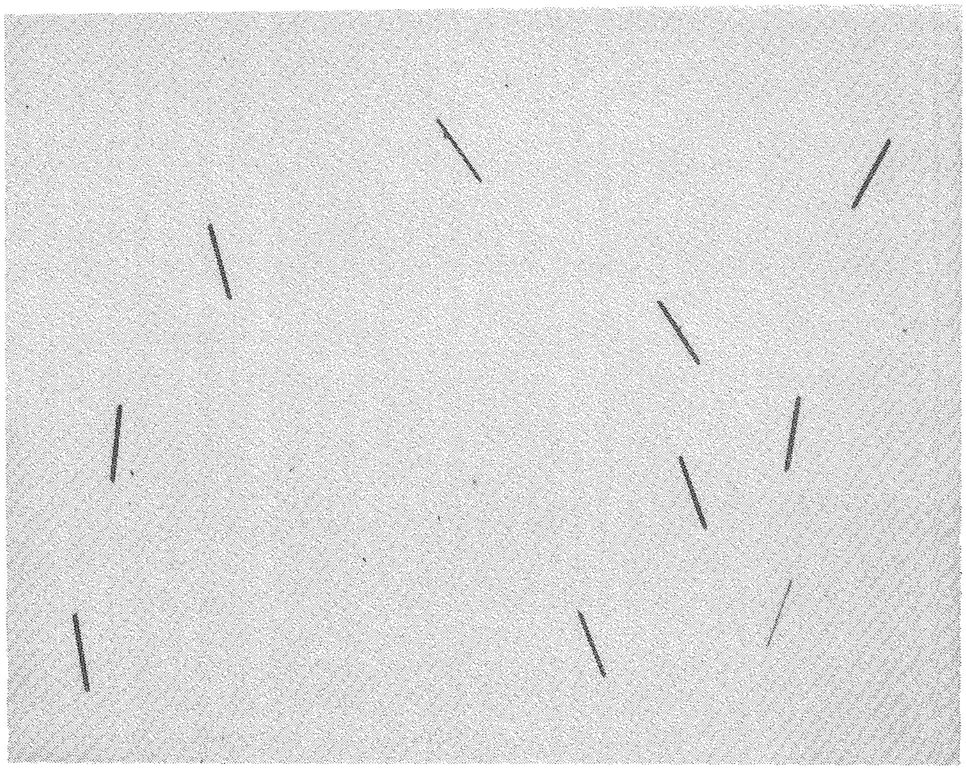

Fig. 5. 237 μm fibers.

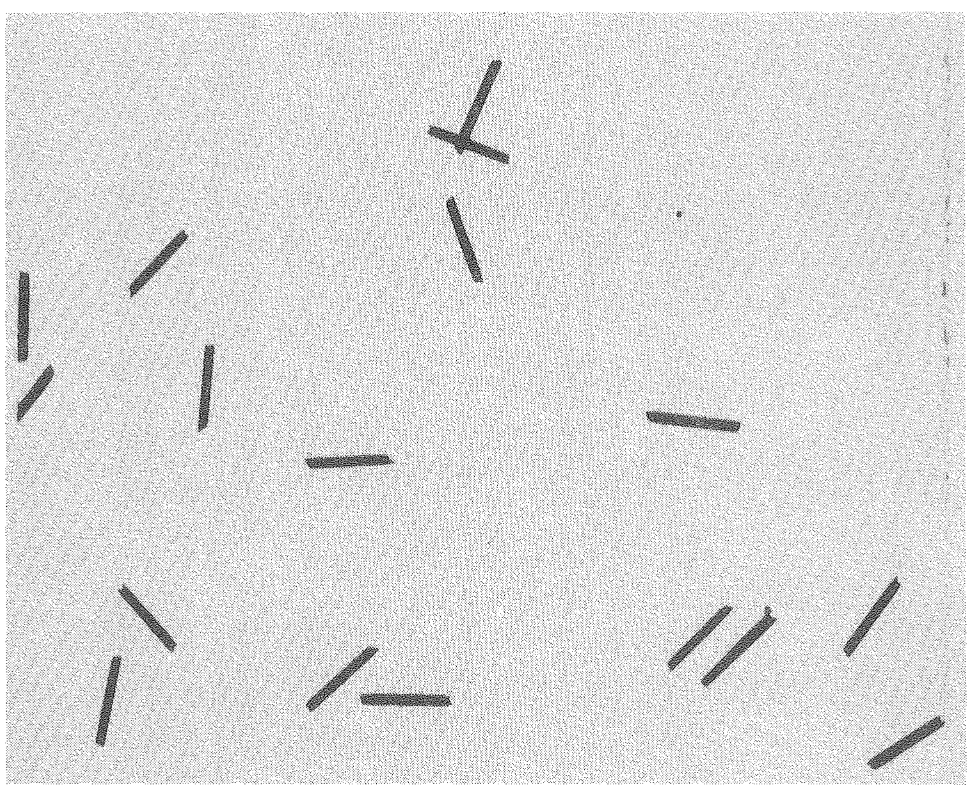

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Fig. 6. 111 μm fibers.

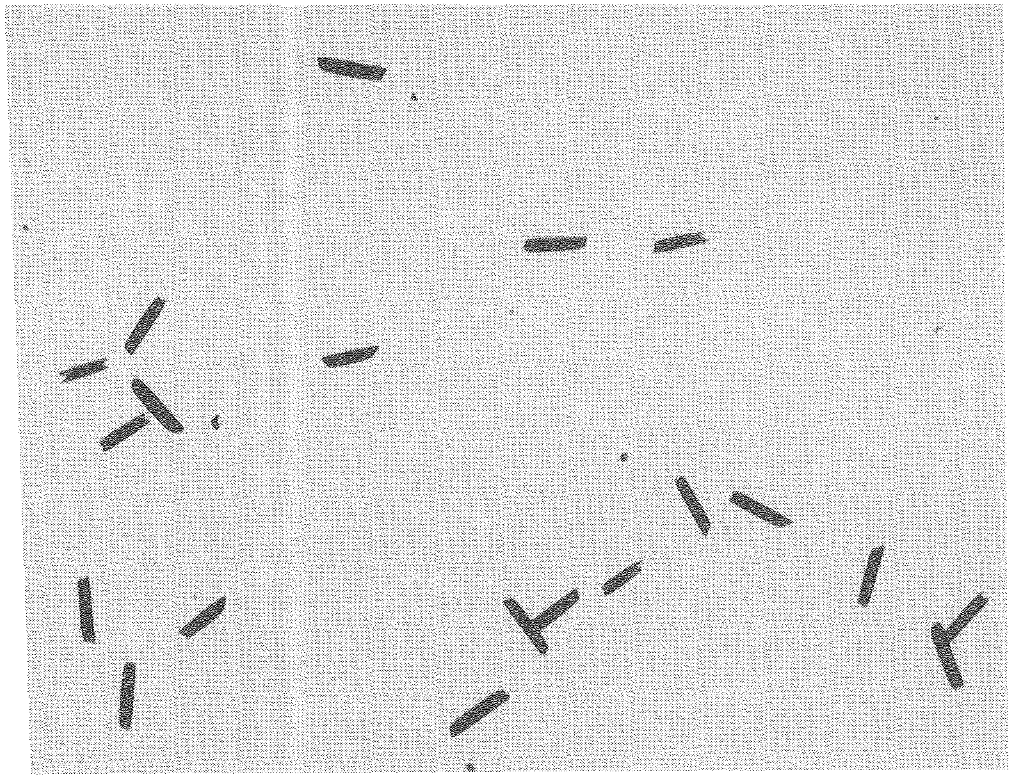

Fig. 7. 44 μm fibers.

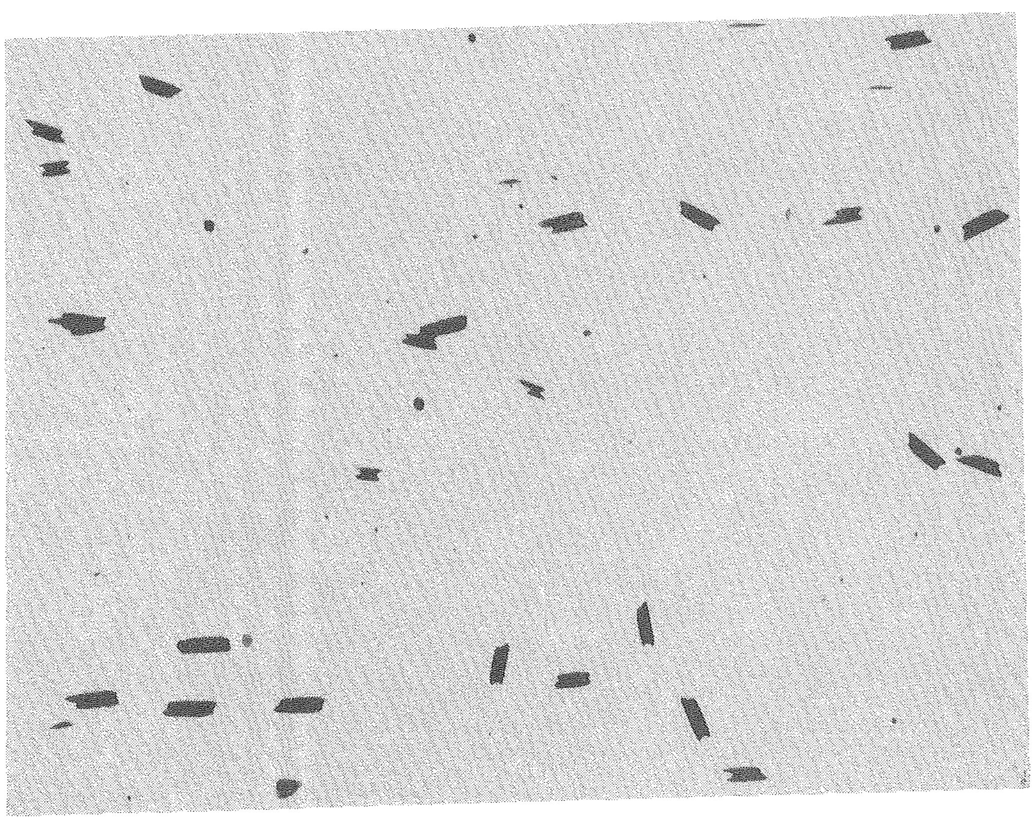

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Fig. 8. 32 μm fibers.

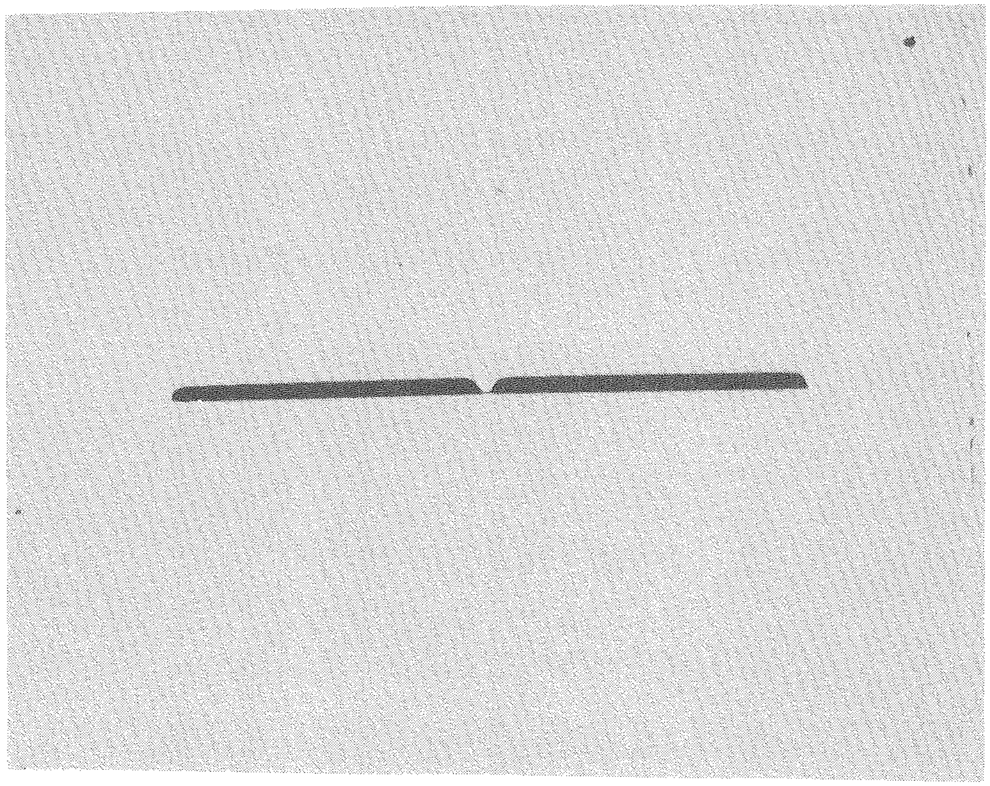

Fig. 9. Size of beam spot as revealed by an incomplete cut.

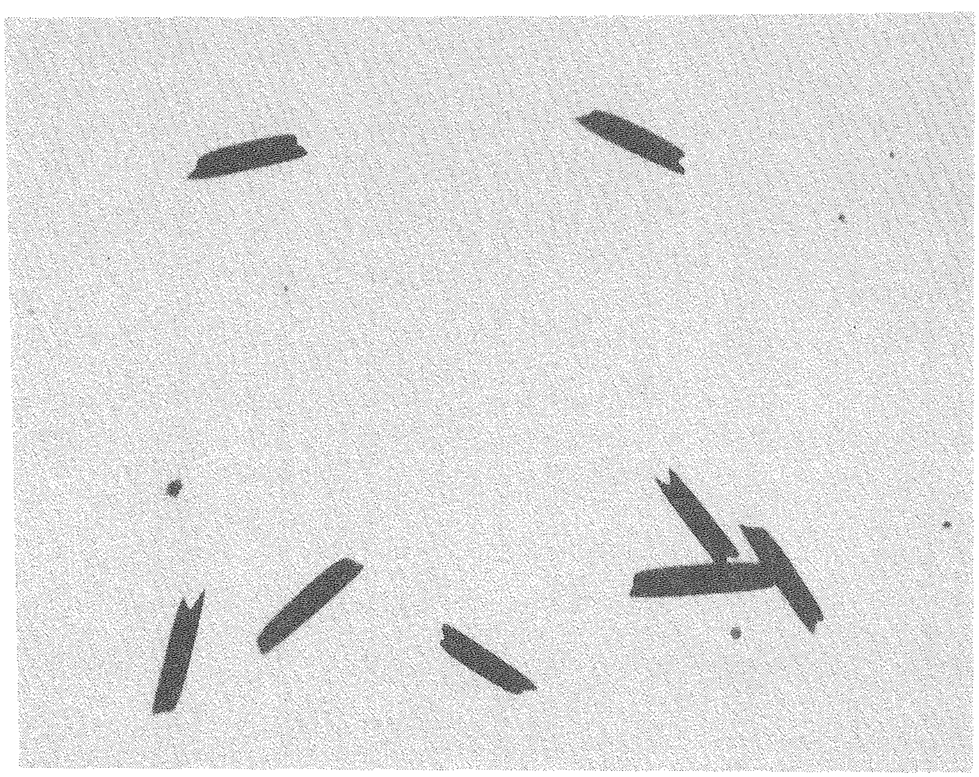

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Fig. 10. Details of cut fibers.